Worsening Radiation Environment

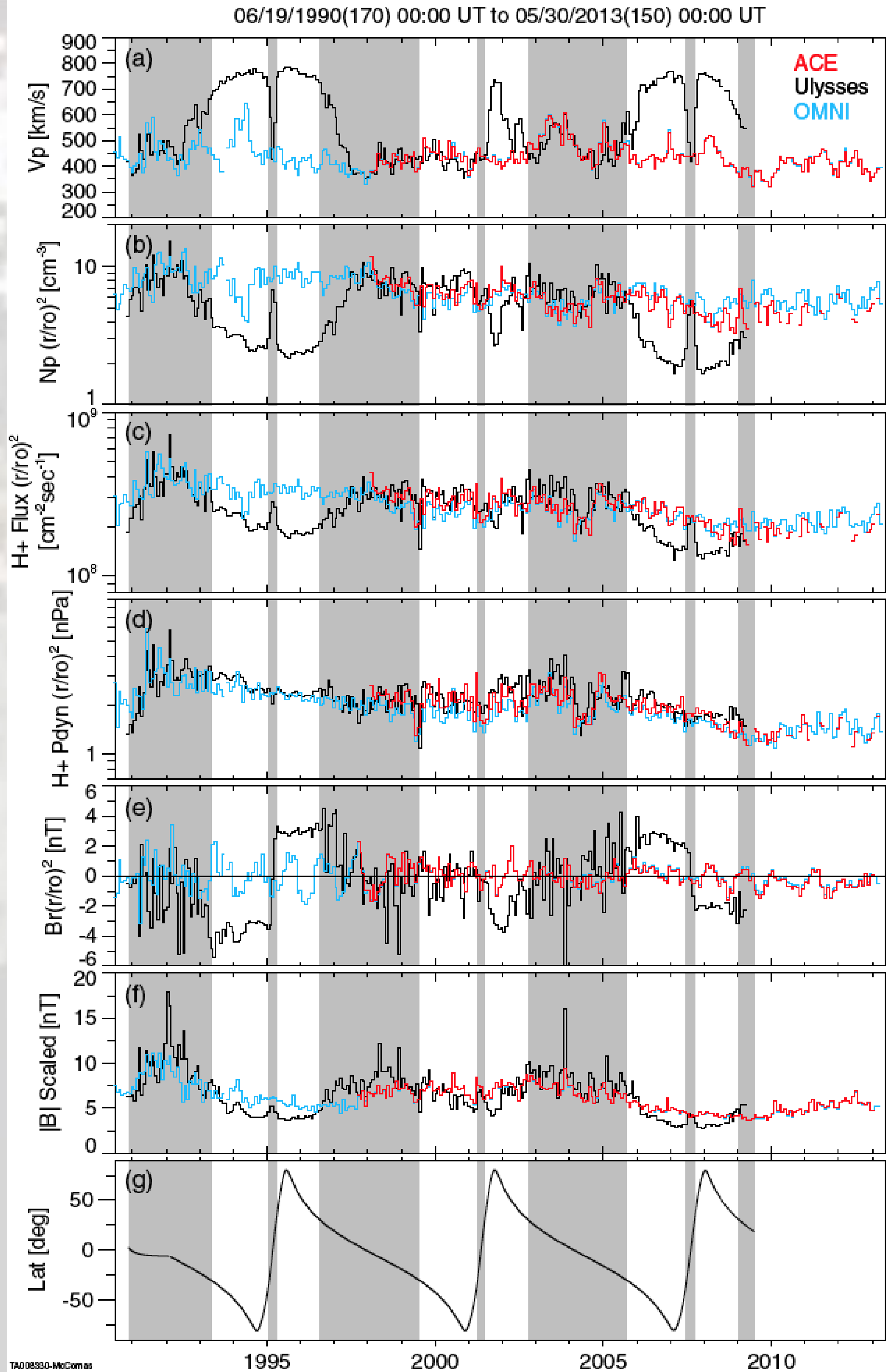
N. A. Schwadron[1], J. B. Blake[2], A. W. Case[3], C. Joyce[1], J. Kasper[3,4], J. Keller[5], J. Mazur[2], N. Petro[5], M. Quinn[1], C. Smith[1], S. Smith[1], H. E. Spence[1], L. Townsend[3], J. K. Wilson[1], C. Zeitlin[7]

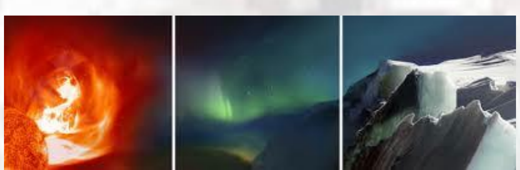
.

Protracted Min (23) and Mini Max (24)

- *Dropping solar wind*
  - *Flux*
  - *Pressure*
  - *Magnetic Field*
- *Continues trend observed by Ulysses*

McComas et al., ApJ, 2013



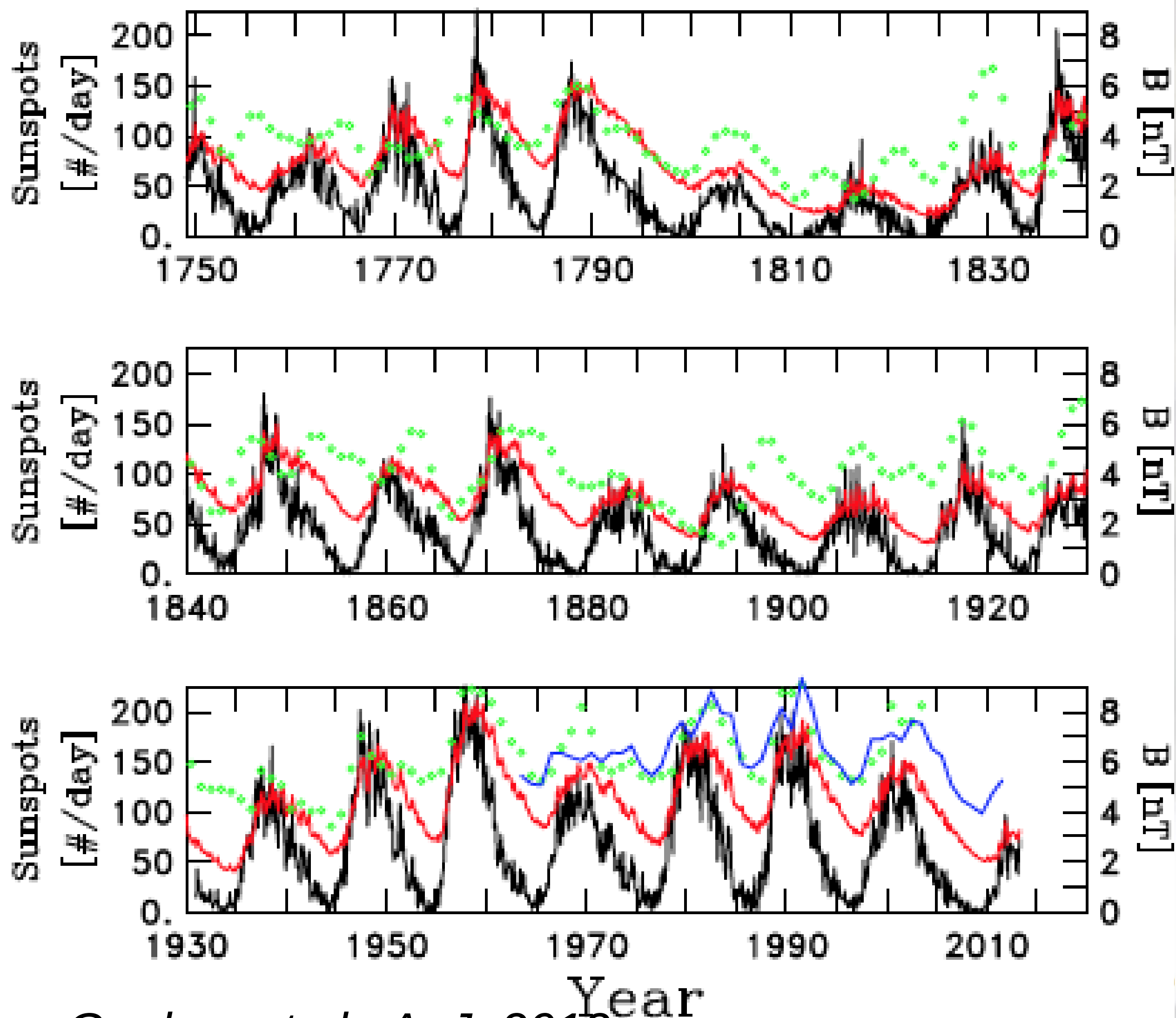


Reductions in Magnetic Field & SSN

- *SSN (black)*
- *Predicted (red)*
- *OMNI (blue)*
- *^{10}Be (green)*
- *Magnetic Flux Balance (Schwadron et al.,, 2010)*

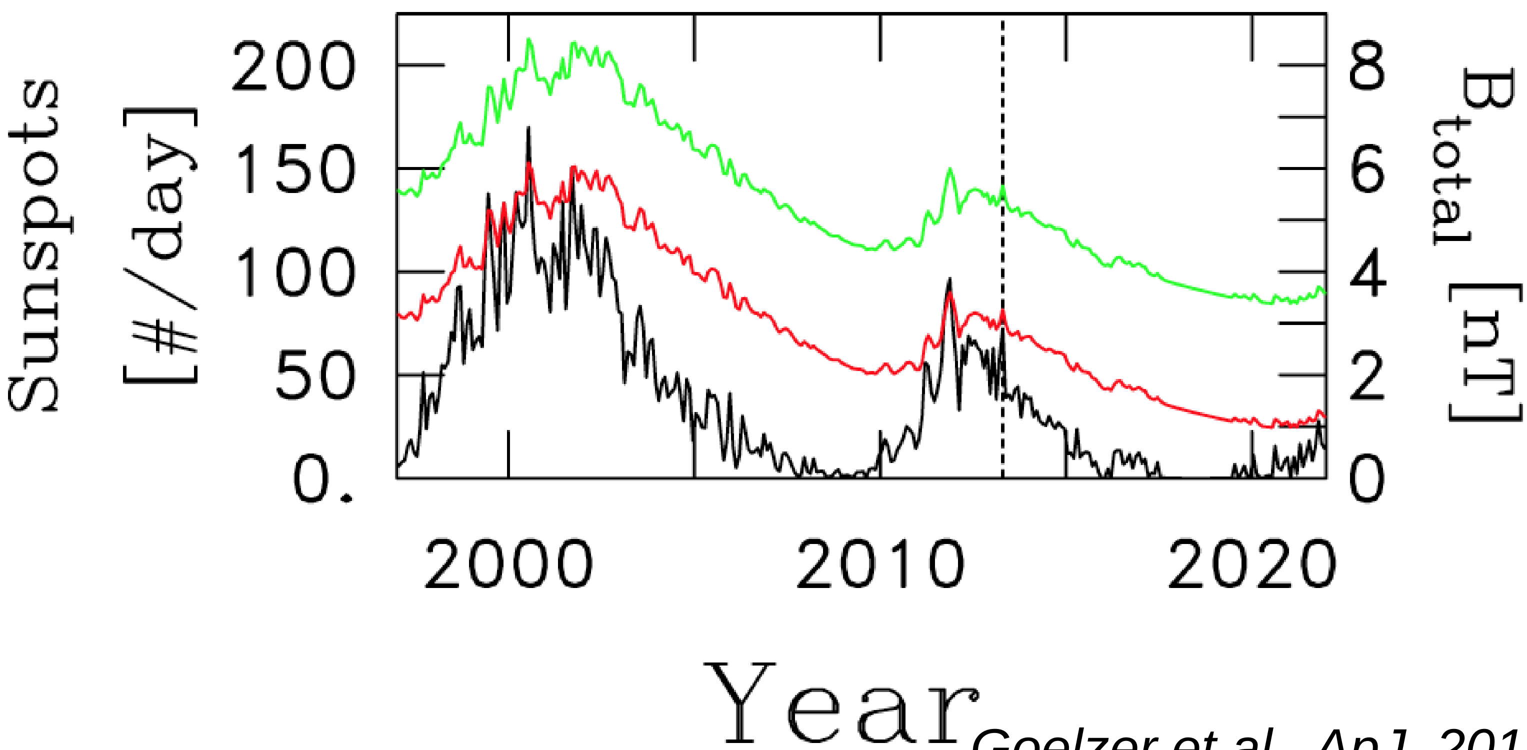
$$\frac{d\Phi_{ej}}{dt} = f\,(1-D)\,\phi_{CME} - \Phi_{ej}\left(\frac{1}{\tau_{ic}} + \frac{1}{\tau_d} + \frac{1}{\tau_o}\right)$$

$$\frac{d\Phi_o}{dt} = -\frac{\Phi_o - \Phi_{flr}}{\tau_d} + \frac{\Phi_{ej}}{\tau_o}.$$



Goelzer et al., ApJ, 2013

Continued Decay of Magnetic Flux in the Dalton-like Minimum



Goelzer et al., ApJ, 2013

Slab Turbulence Model

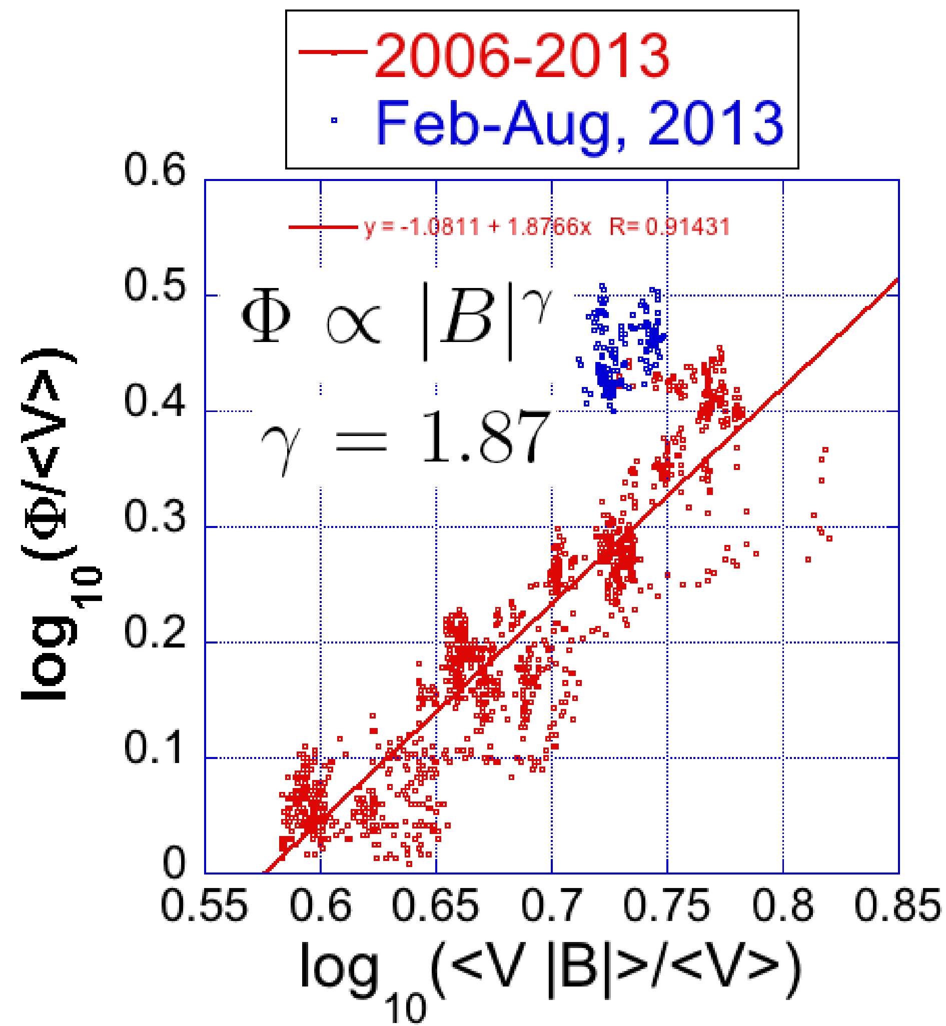
- Modulation Potential

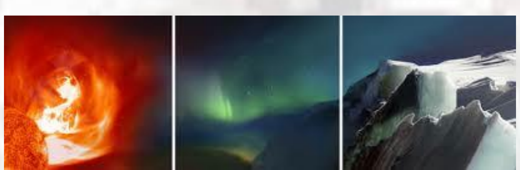
$$\Phi = |Ze|\phi(r)$$

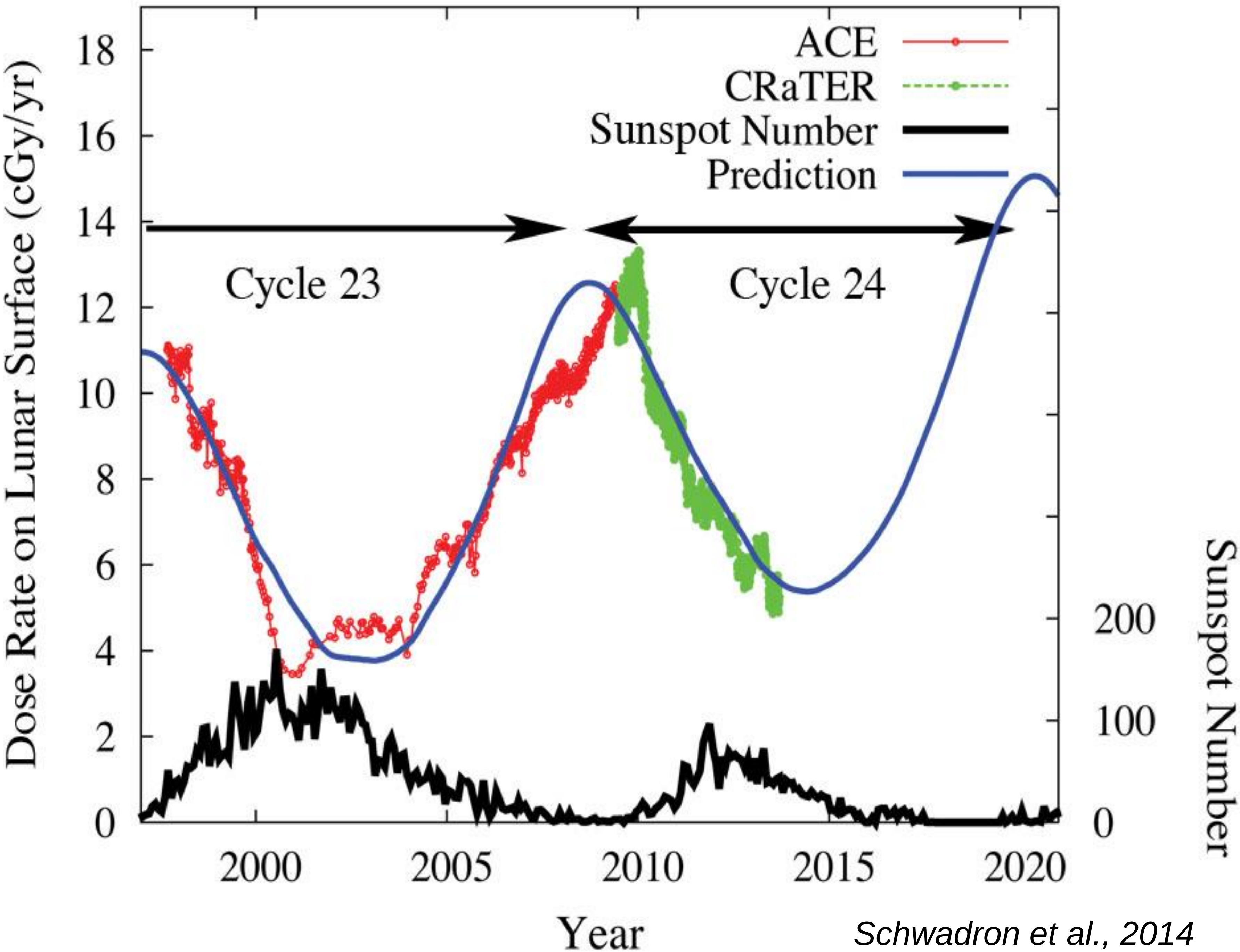
$$\phi(r) = \int_r^{R_b} dx \frac{V(x)}{3\kappa_1(x)}$$

$$\kappa_{||} \propto r_g^2/F^2 \quad F = \delta B/B$$

$$\Phi \propto B^2$$





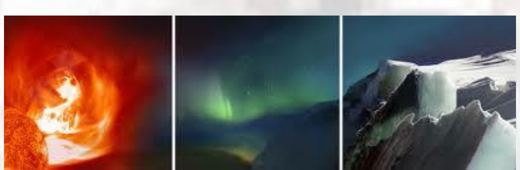


Schwadron et al., 2014

3% Risk for Exposure Induced Death

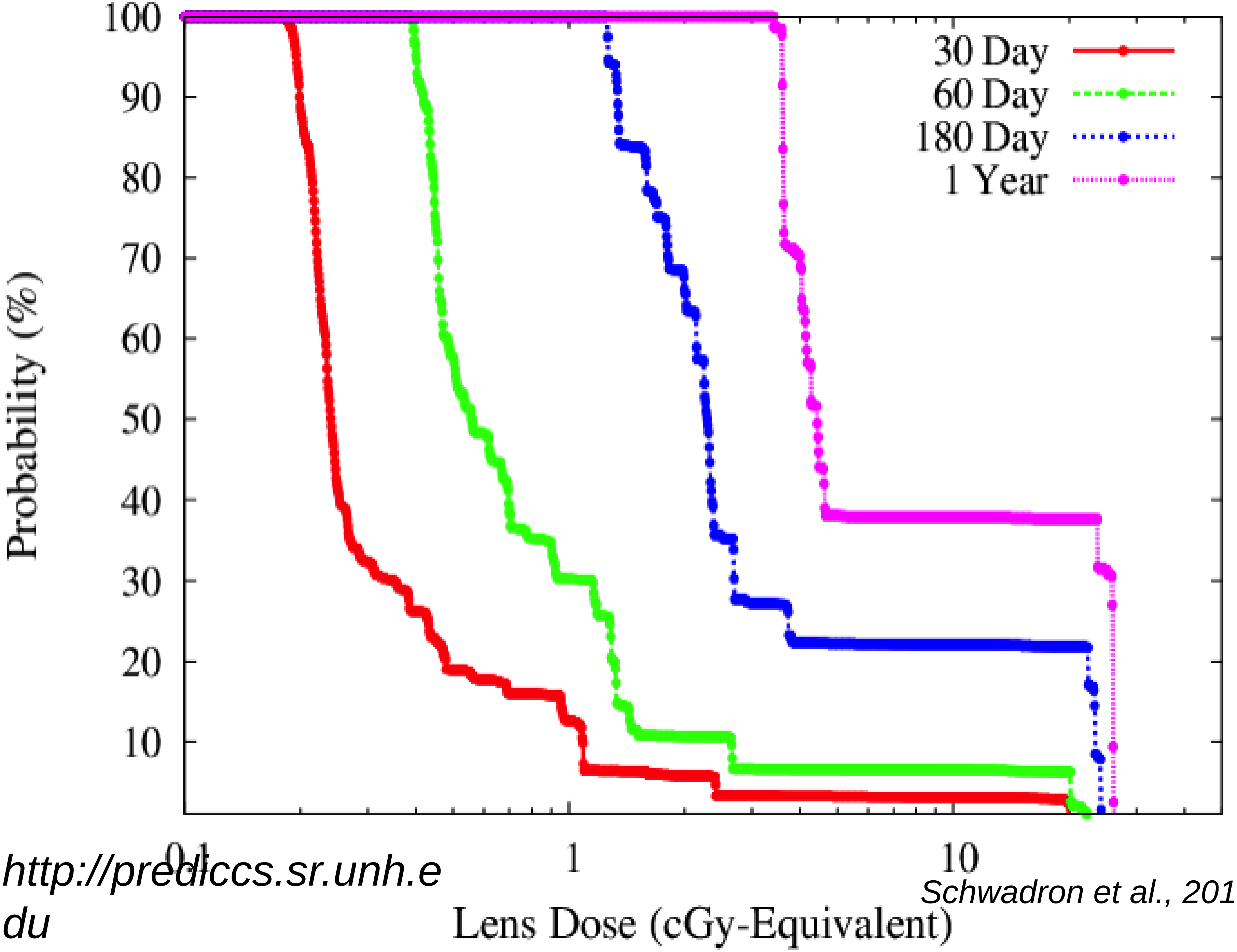
Age	3% REID Maies E (cSv)	3% REID Femails E (cSv)
30	62	47
45	95	75
55	147	112

Managing Space Radiation Risk in the New Era of Space Exploration
Committee on the Evaluation of Radiation Shielding for Space Exploration, National Research Council 2008



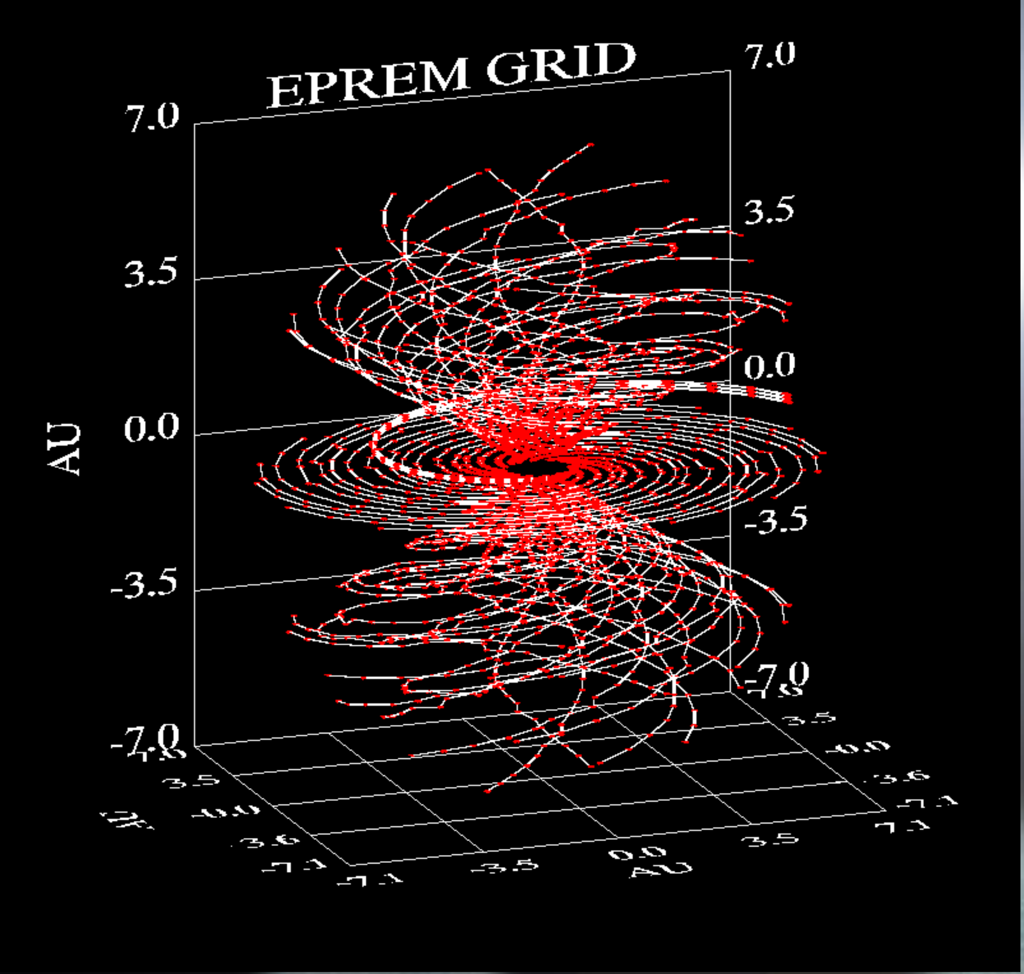
Time (Cycle)	Dose Eq. Rate <Q>=5.8 (cSv/dy)	Days to 3% REID (30 yr old male)	Days to 3% REID (30 yr old female)	Dose Eq. Rate <Q>=3.8 (cSv/dy)	Days to 3% REID (30 yr old male)	Days to 3% REID (30 yr old female)
1997.0 (Min 22-23)	0.35	180	130	0.23	270	200
2003.0 (Max 23)	0.13	490	370	0.08	740	560
2008.7 (Min 23-24)	0.40	155	120	0.26	240	179
2014.0 (Max 24)	0.18	350	270	0.12	530	400
2020 (Min 24-25)	0.47	130	100	0.31	200	150

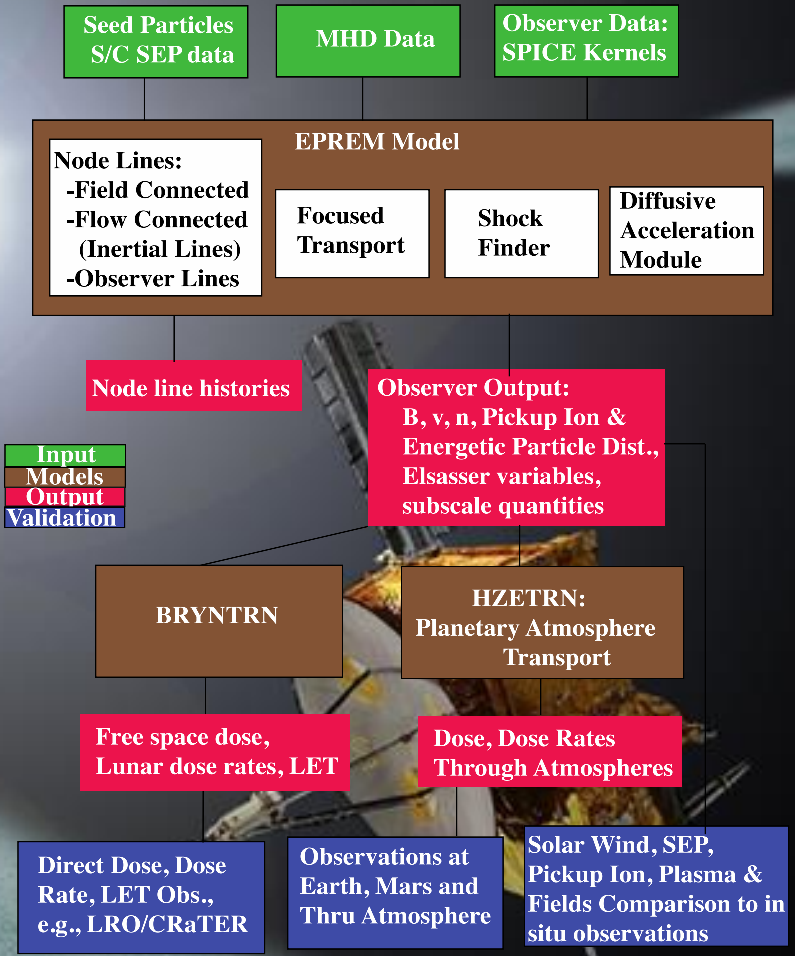
Schwadron et al., 2014



http://prediccs.sr.unh.edu

Schwadron et al., 2014





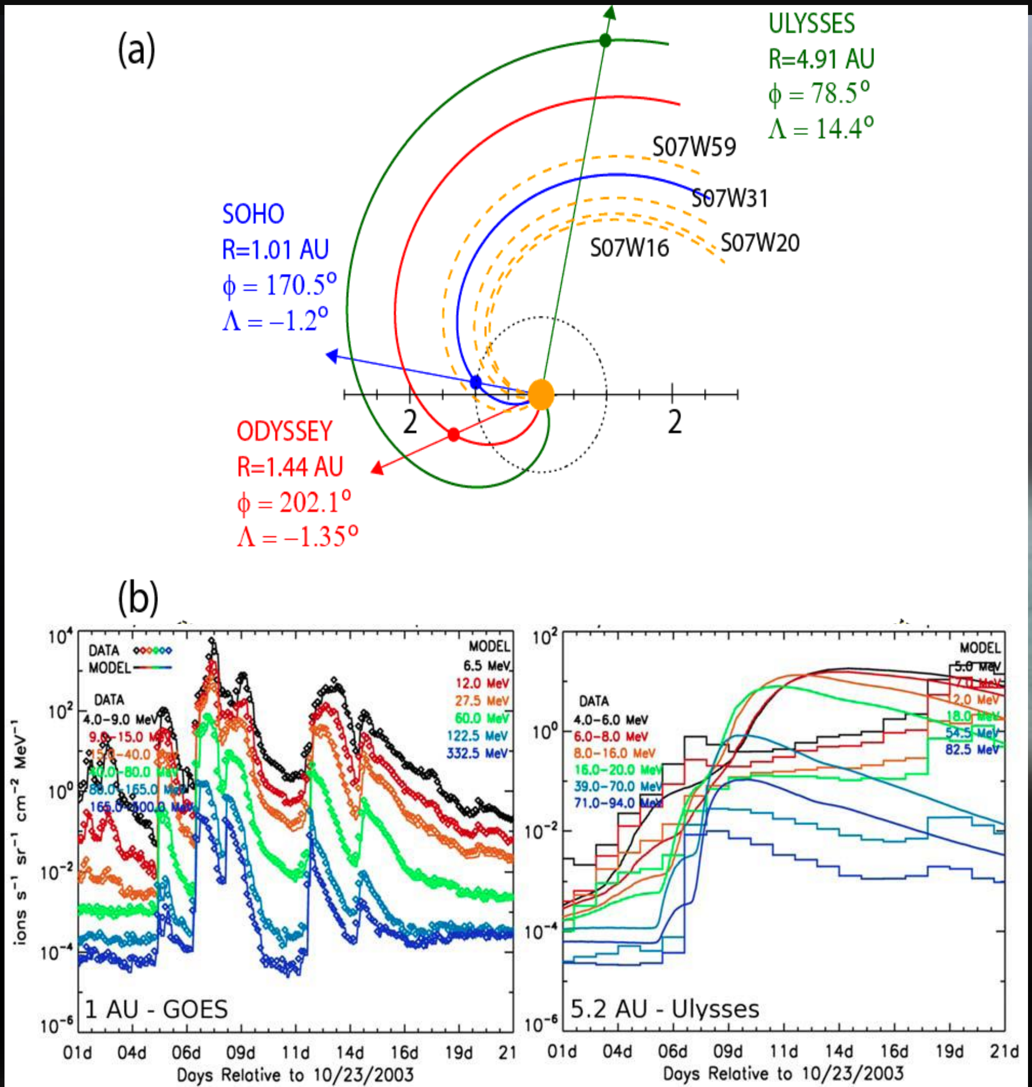
Focused Transport in Lagrangian Frame (Kota, 2005)

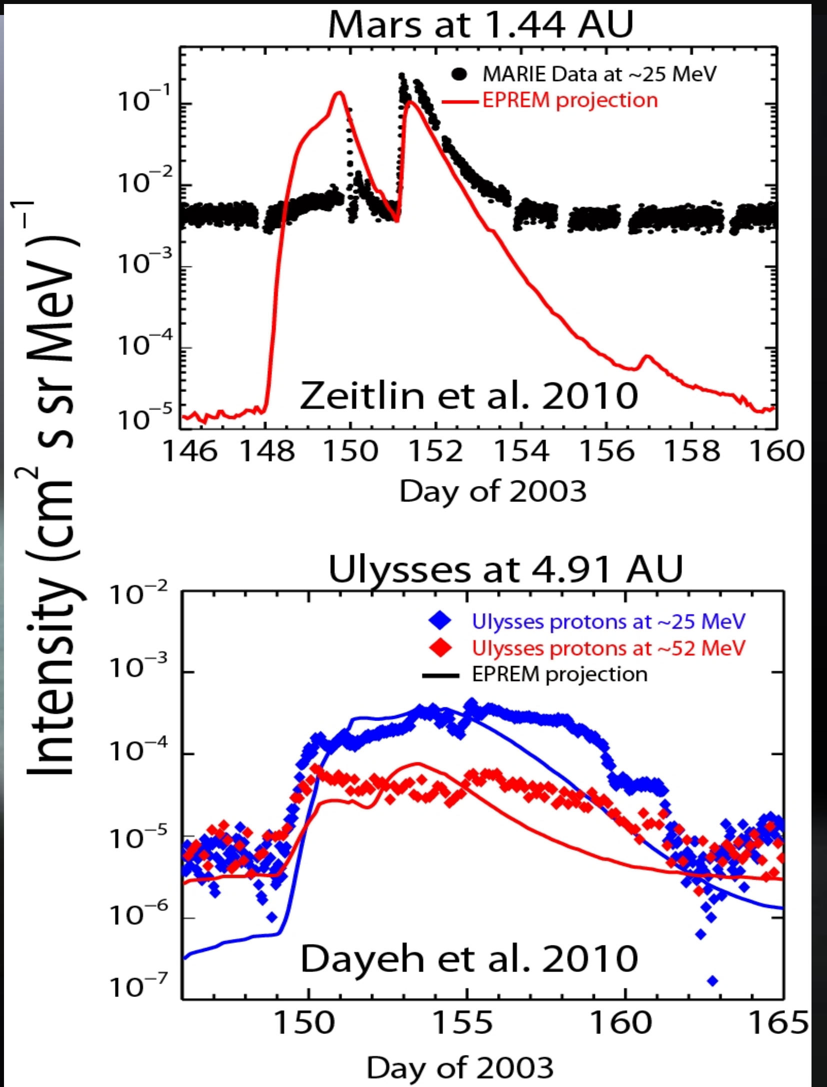
$$\left(1-\frac{(\vec{u}\times e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\times\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$

$$\left[-\frac{\mu e_b}{v}\times\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

- Cross-field Diffusion
- Drift

EMMREM has proved very successful at predicting SEP spectra and radiation dose estimates at different distances in the inner heliosphere. Figures below show two recent papers by which SEP time profiles, onset, and radiation estimates were successfully predicted at Mars (Odyssey) and Ulysses located at 1.44 AU and 4.91 AU, respectively. 1 AU measurement from ACE, SoHO, and GOES.



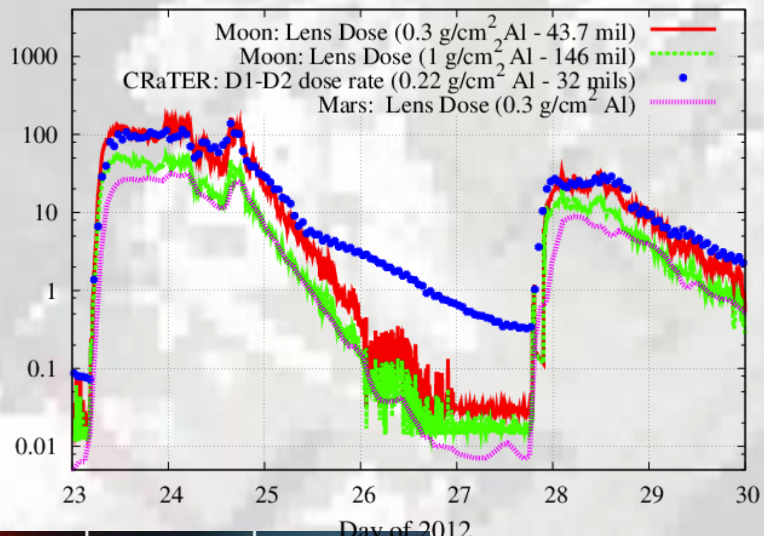


Validation with CRaTER

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

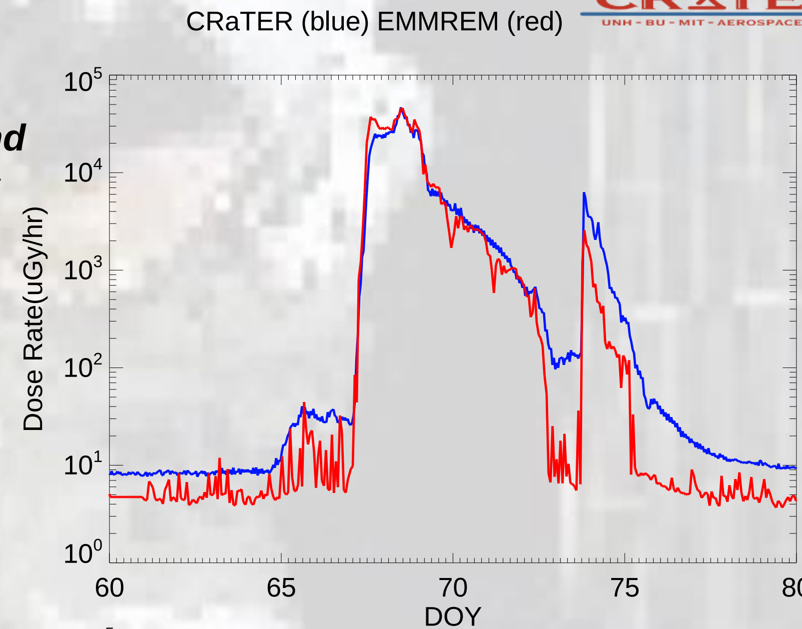
- ***Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and prediccs predictions (red and green).***
- ***Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER***

Jan. 23rd, 2012 Event

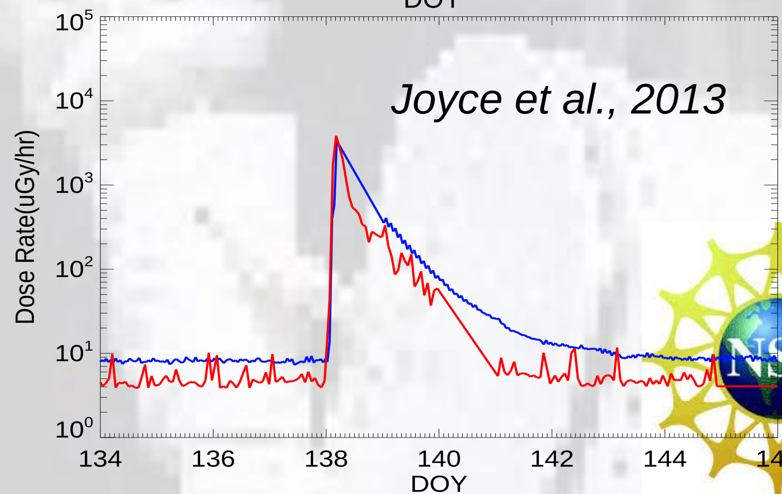


Schwadron et al., 2013

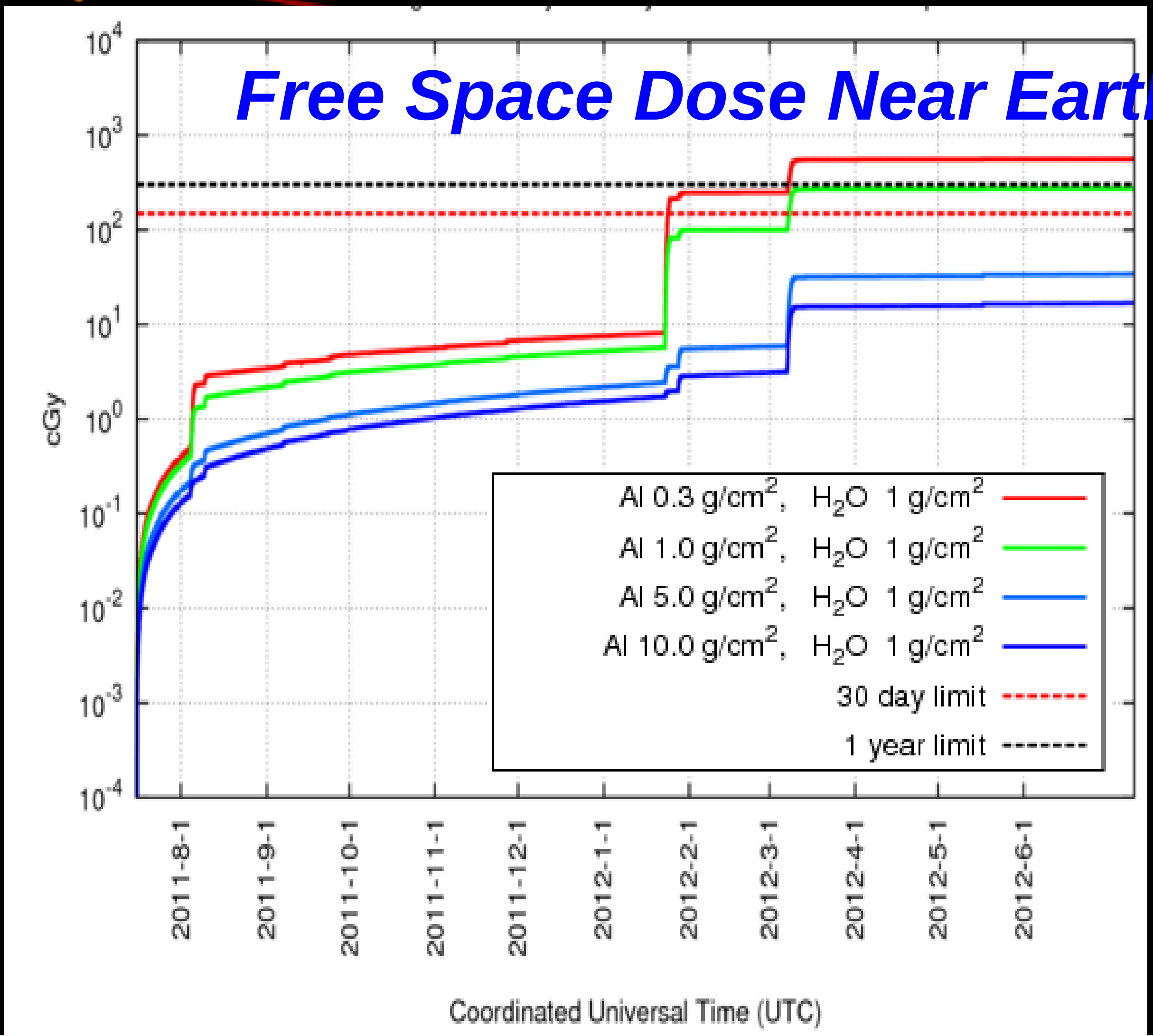
Mar 7, 2012 Event



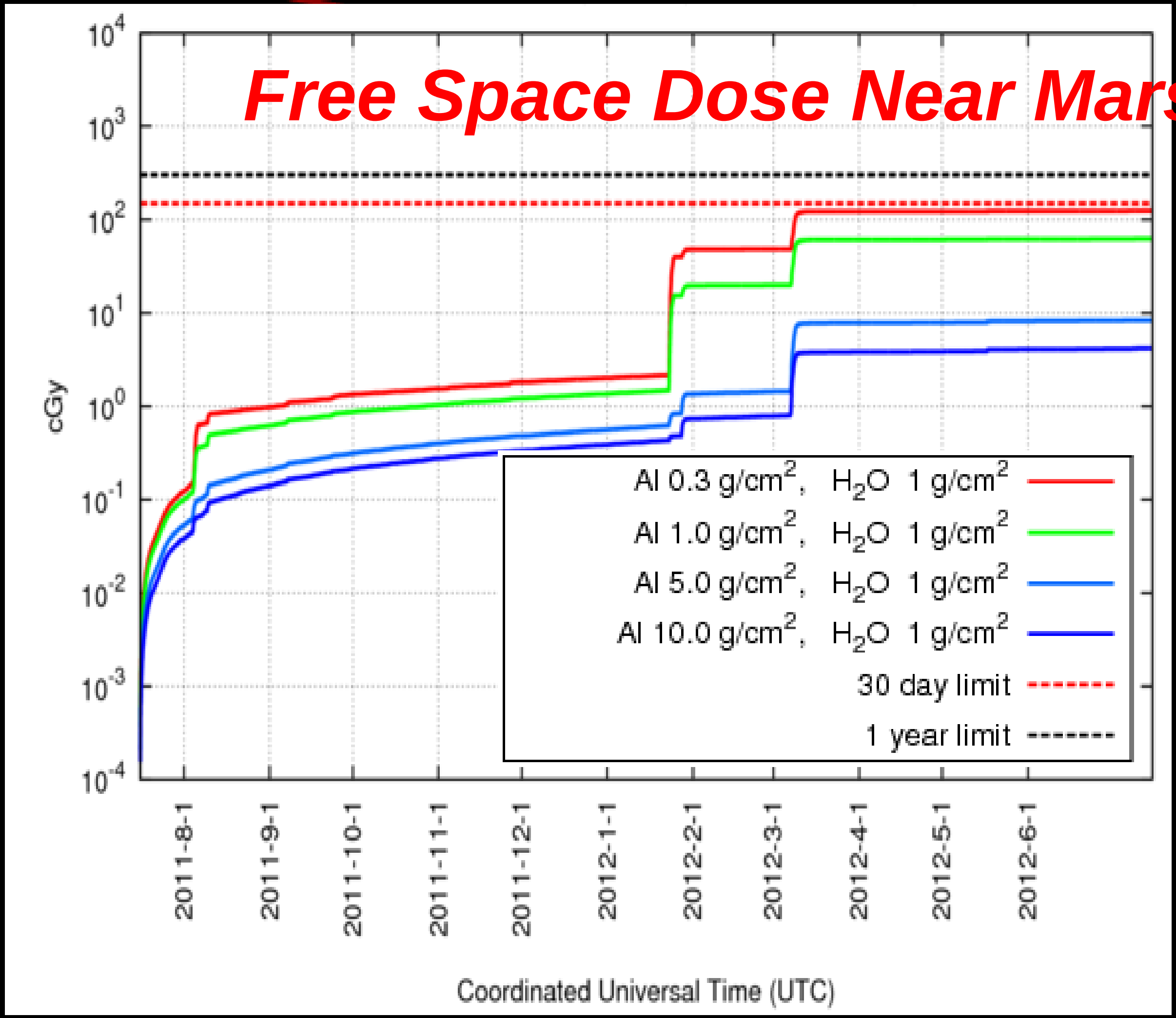
May 16, 2012 Event



- System for Radiation Environment characterization (fluxes, doses, dose equivalents at Earth, Moon and Mars) on hourly thru yearly time frame
- Example: Snapshots of Current Yearly Doses at Earth and Mars
- Note: Exceeding 1-yr Free Space Dose Limits at Earth and Moon for < 1 g/cm² Al Shielding
- See more at http://prediccs.sr.unh.edu/



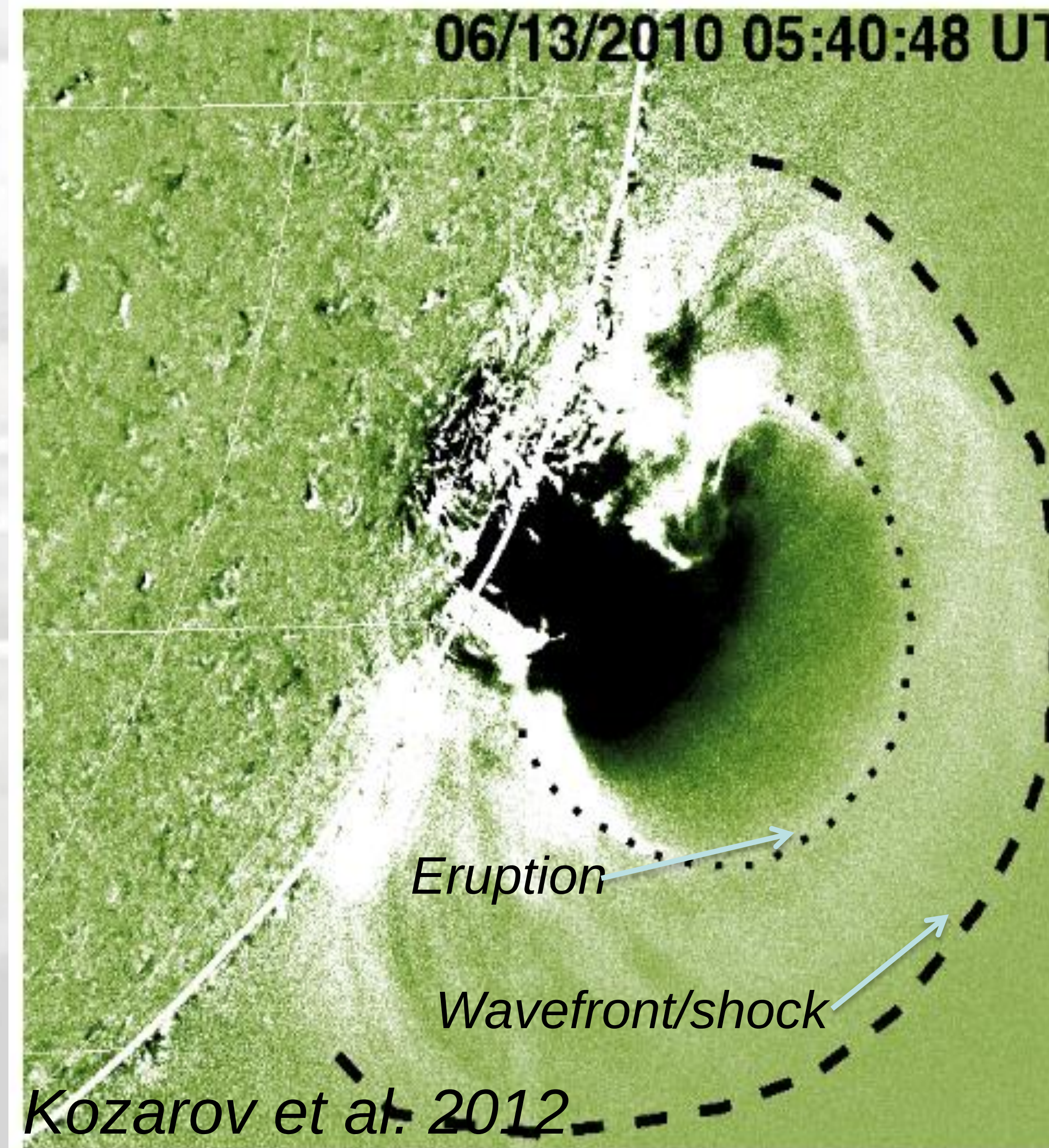
- *Approaching 1-yr Free Space Dose Limits at Mars*
- *See more at http://prediccs.sr.unh.edu/*



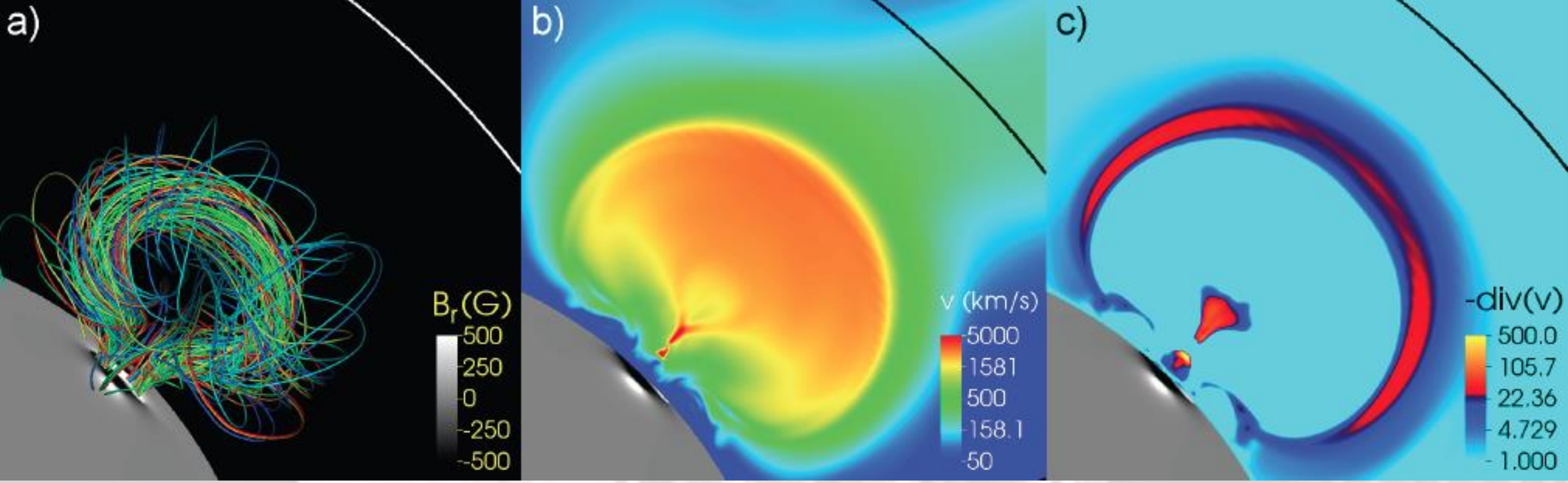
Remote Observations Showing Events from the Low Corona

Formation of acceleration regions (from shocks and compressions) in the low corona critical missing piece in understanding sudden SEP onsets.

- AIA/211 image shows a stage of the 2010 June 13 coronal wave with
- The shock was formed at ~1.2 Rs and observed here at 1.4 Rs.



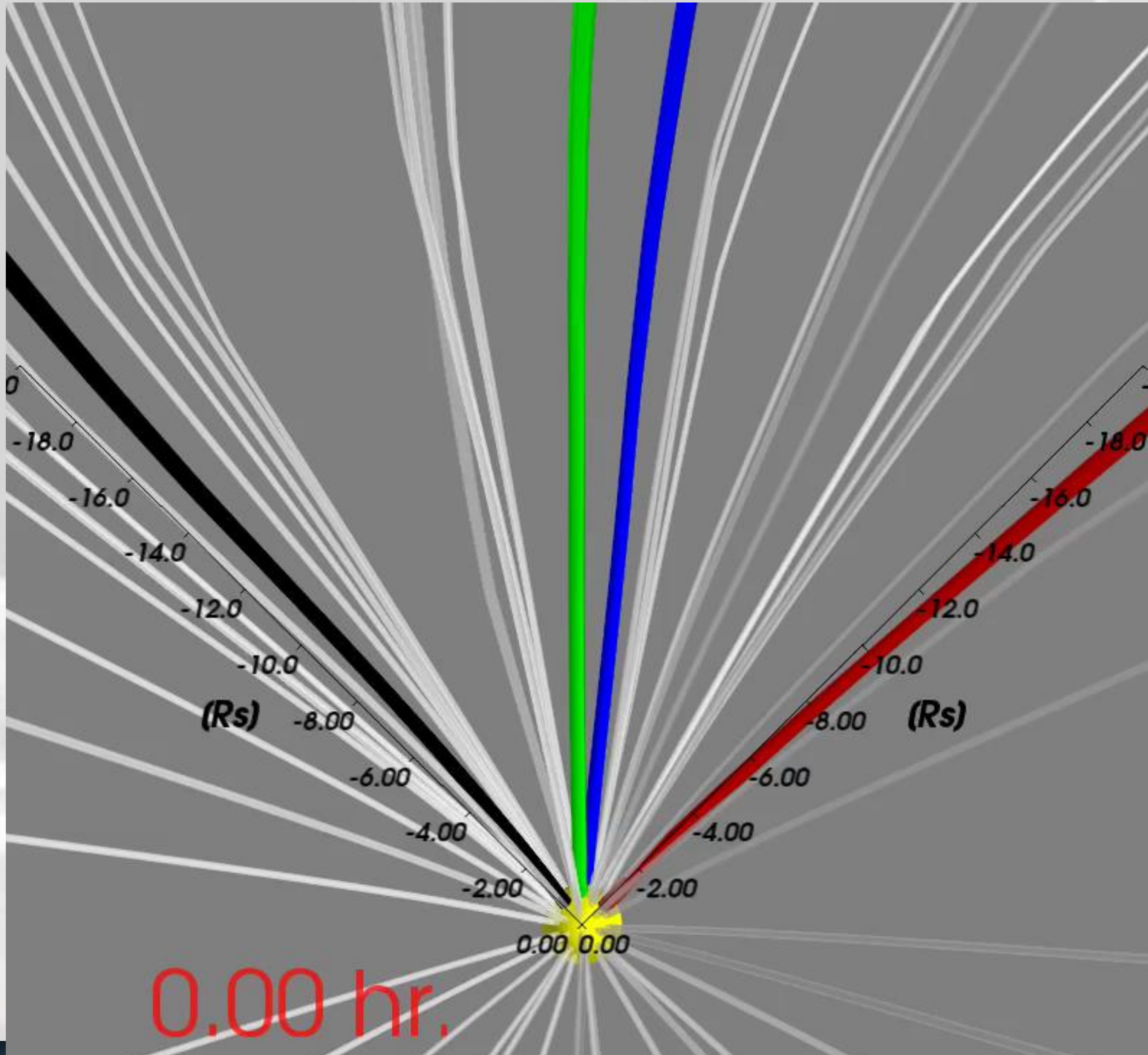
Kozarov et al. 2012



Titov et al., 2013

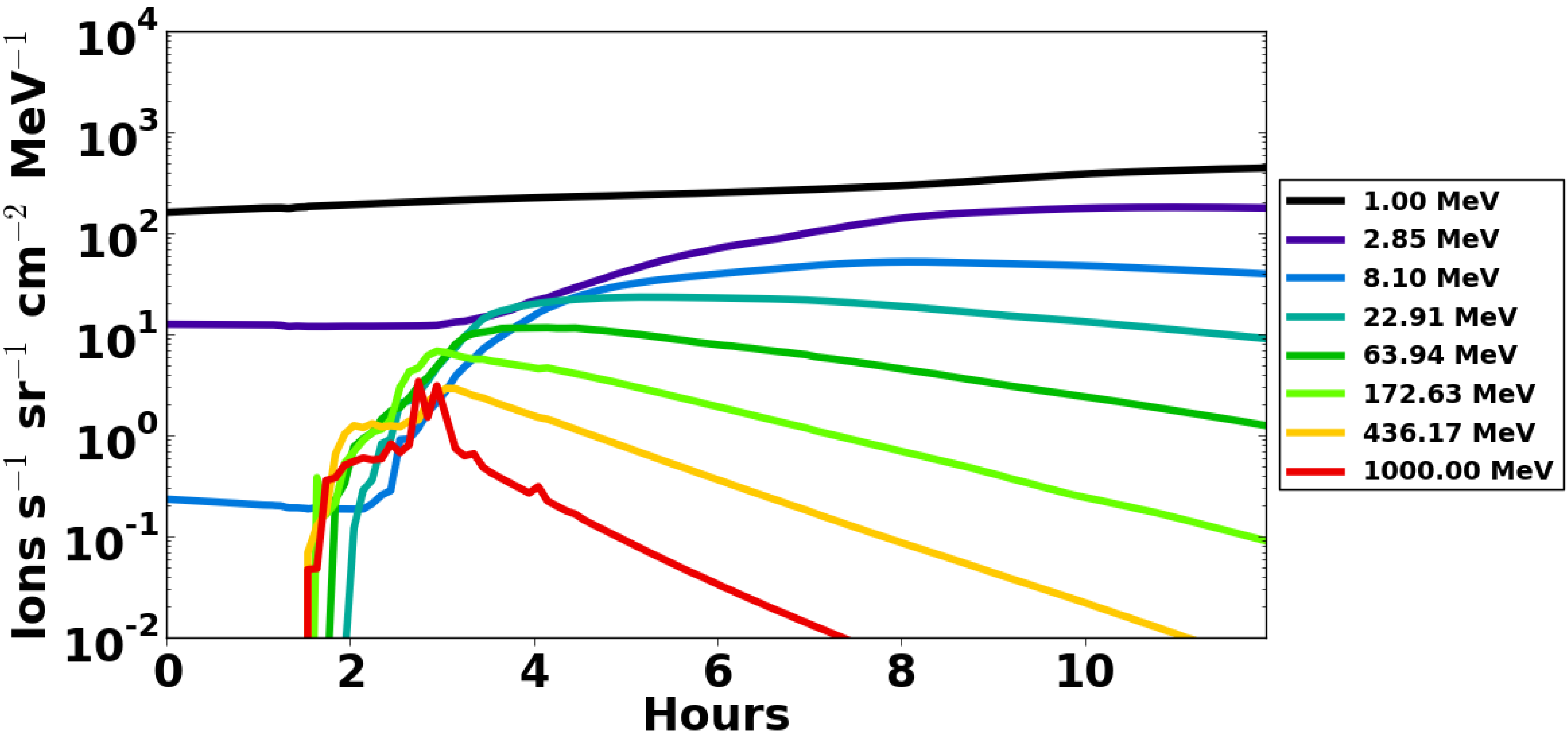
- Insert modified version of the flux rope model by Titov & Demoulin (1999) above the central polarity inversion line of AR.
  - AR + Flux Rope total unsigned flux of 7.5×10^{22} Mx
  - Max radial-field strength of 1070 G at the photospheric level

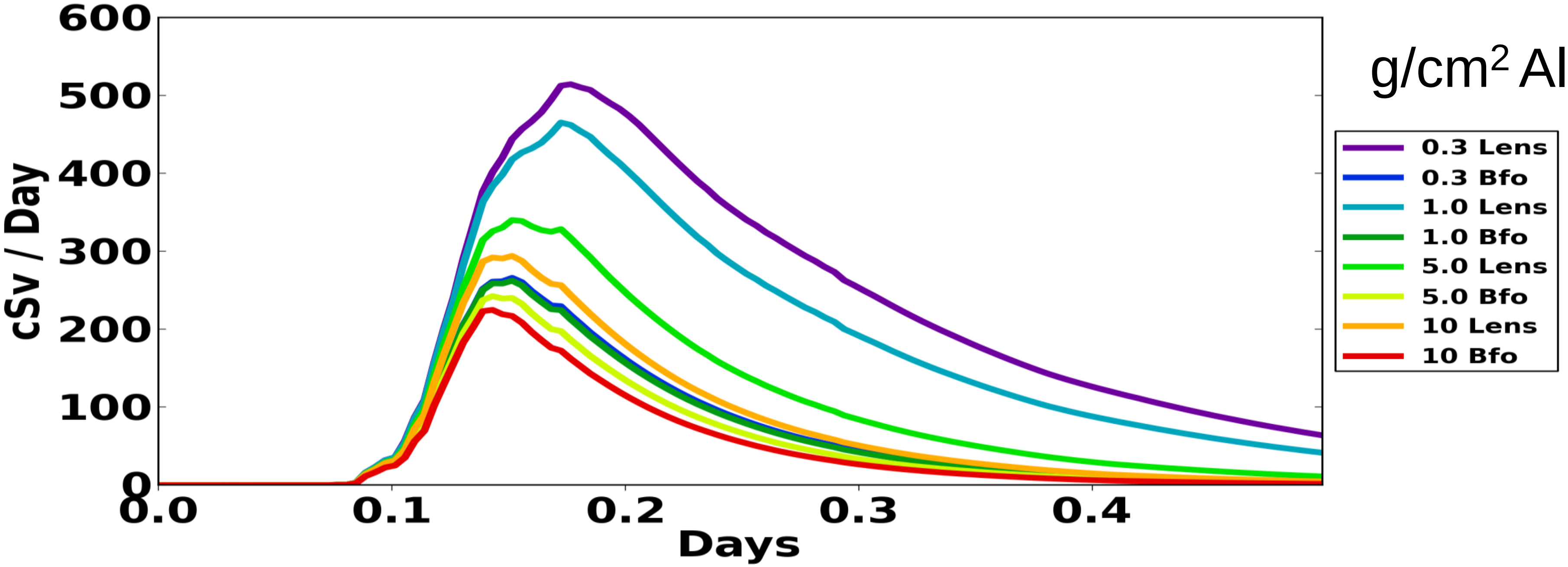
- a

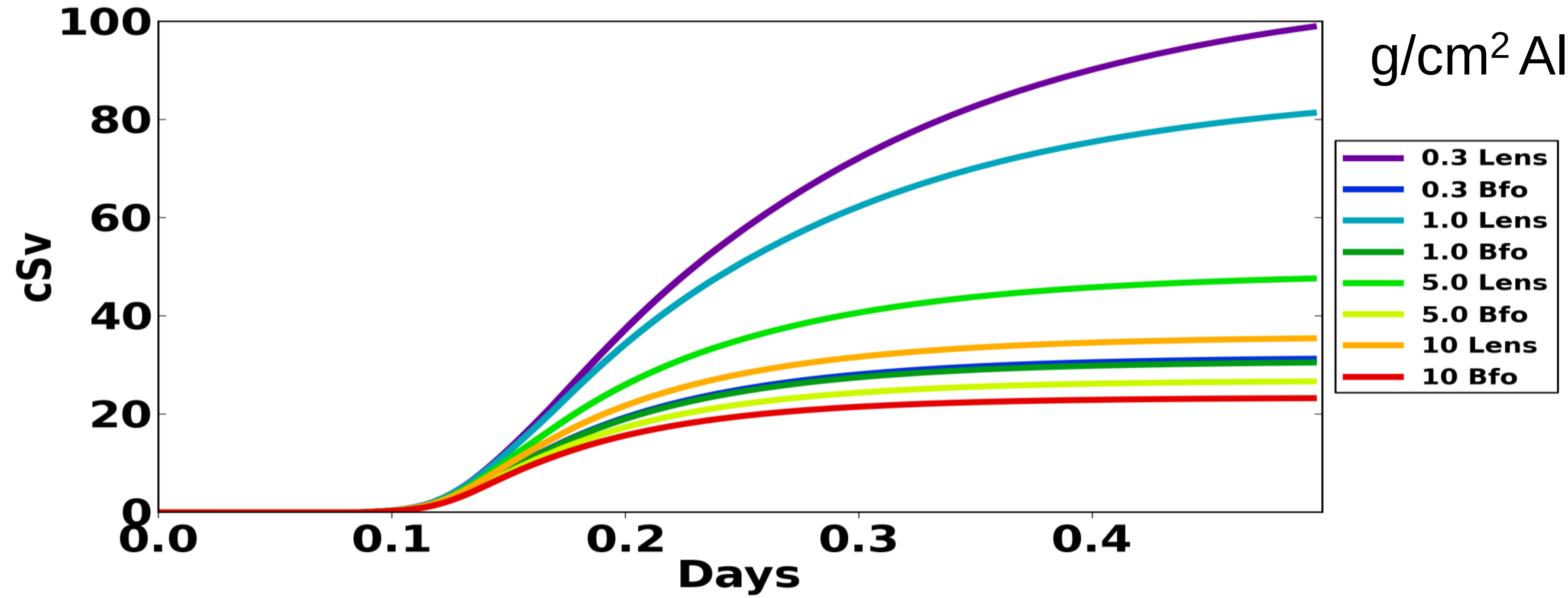


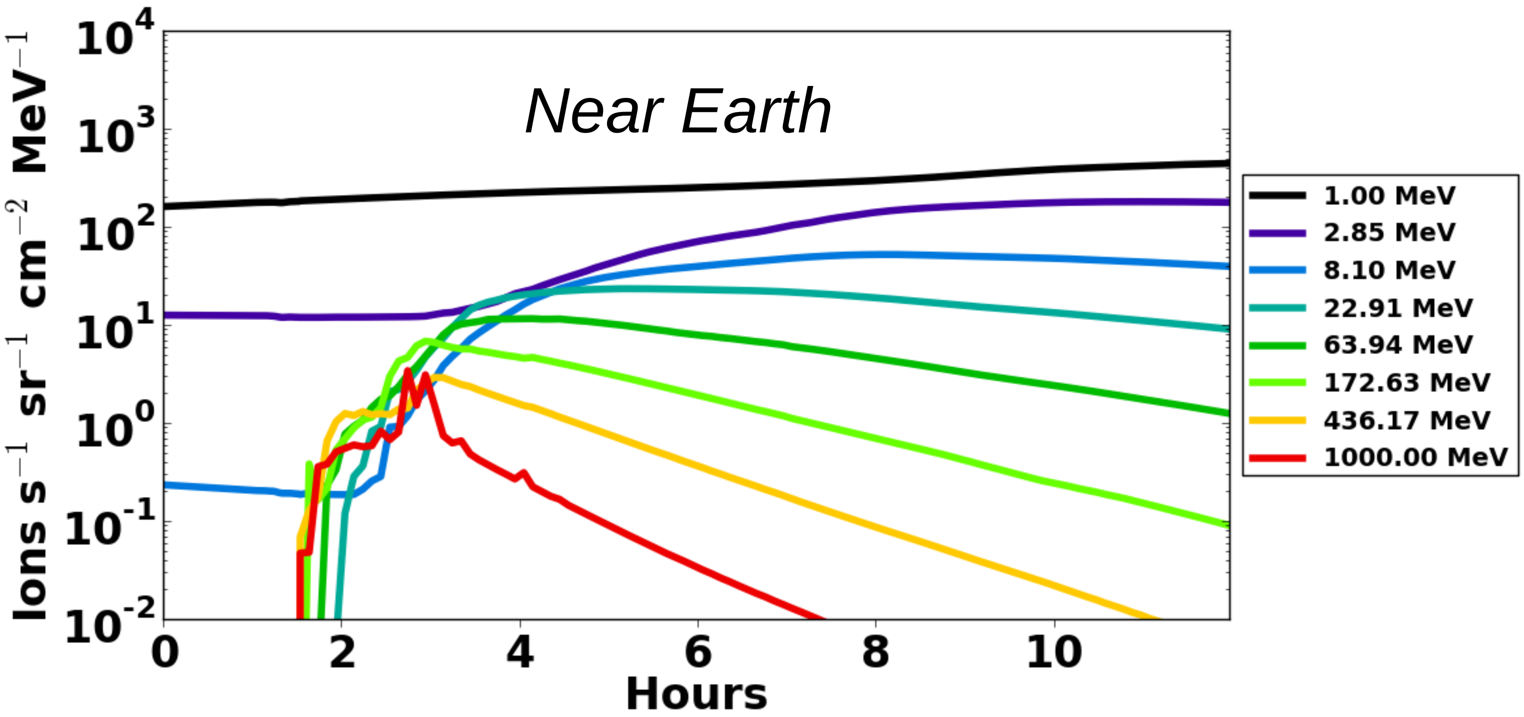
-18.0
-16.0
-14.0
-12.0
-10.0
(Rs)
-8.00
-6.00
-4.00
-2.00
0.00
0.00
-18.0
-16.0
-14.0
-12.0
-10.0
-8.00
(Rs)
-6.00
-4.00
-2.00
0.00 hr.

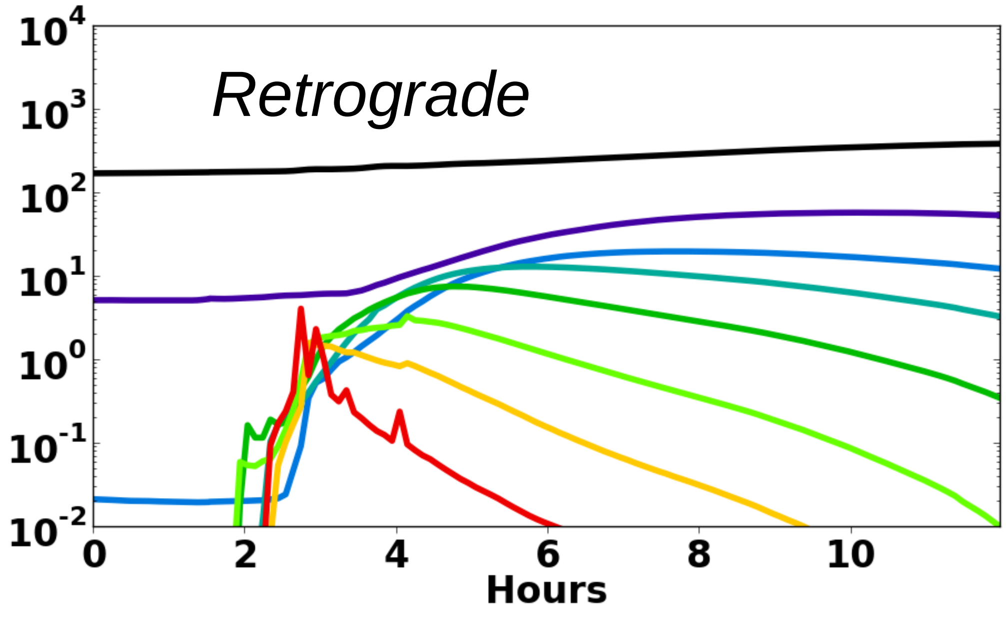
Earth Observer

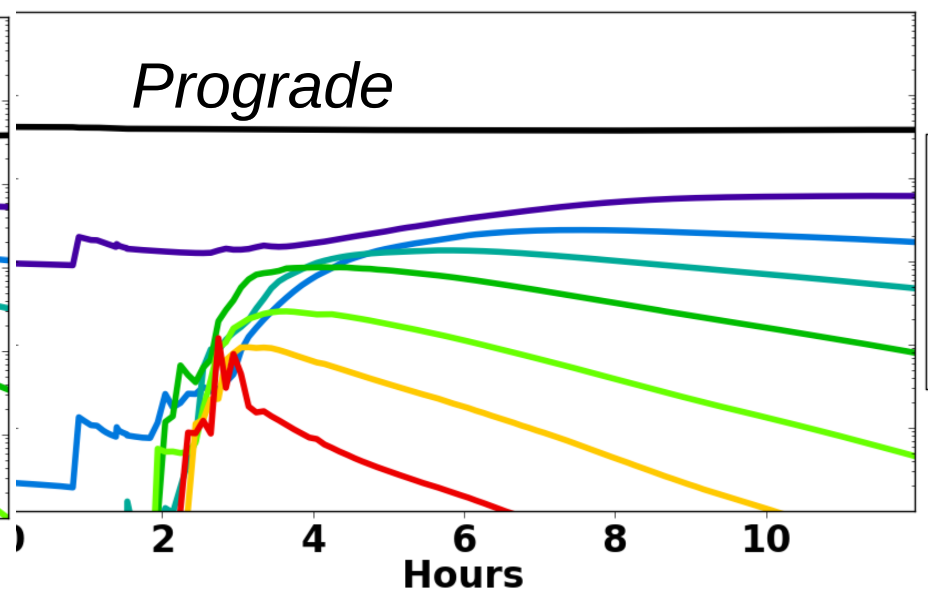


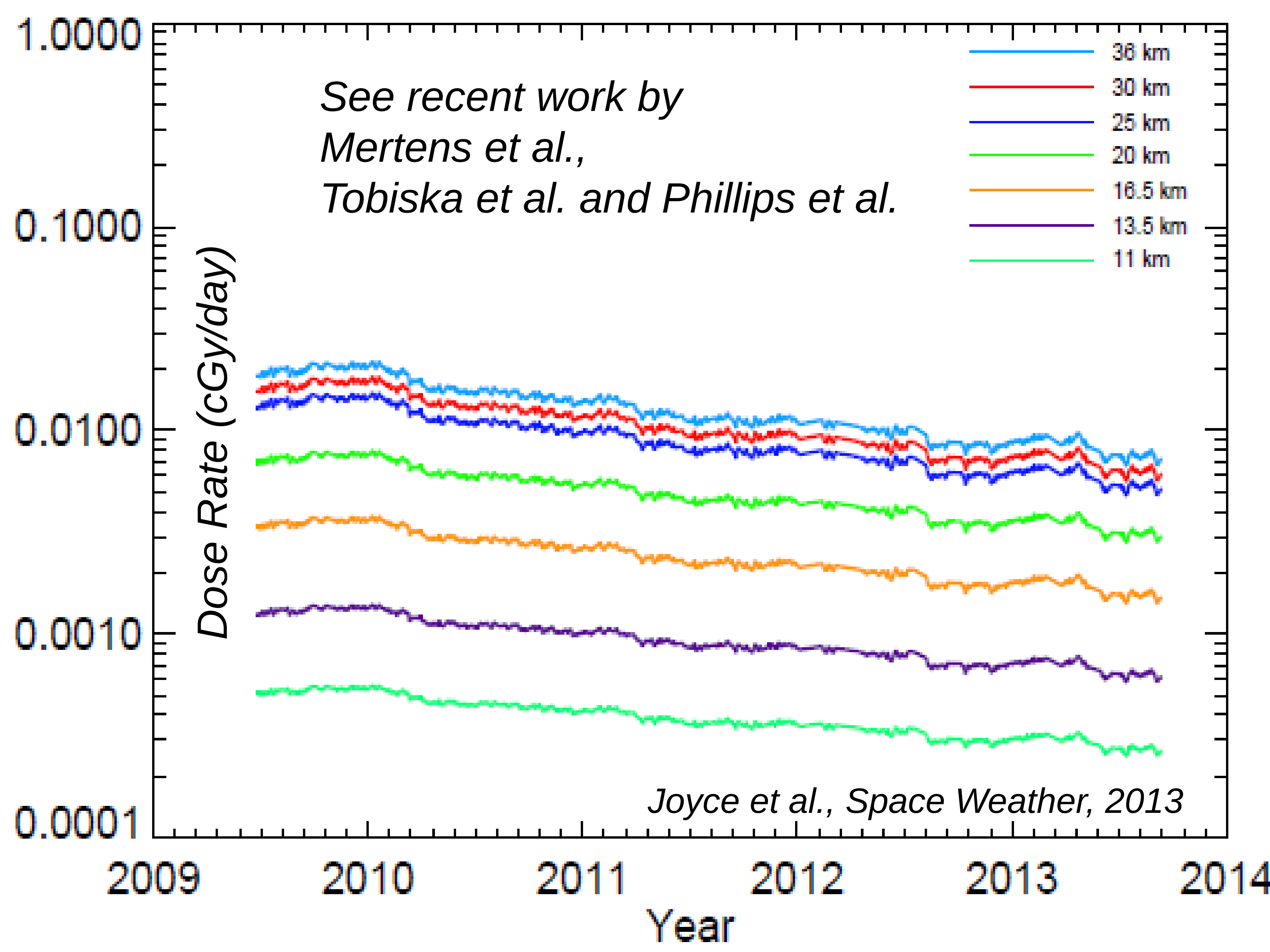

g/cm^2 Al
0.3 Lens
0.3 Bfo
1.0 Lens
1.0 Bfo
5.0 Lens
5.0 Bfo
10 Lens
10 Bfo
cSv / Day
Days
600
500
400
300
200
100
0
0.0
0.1
0.2
0.3
0.4

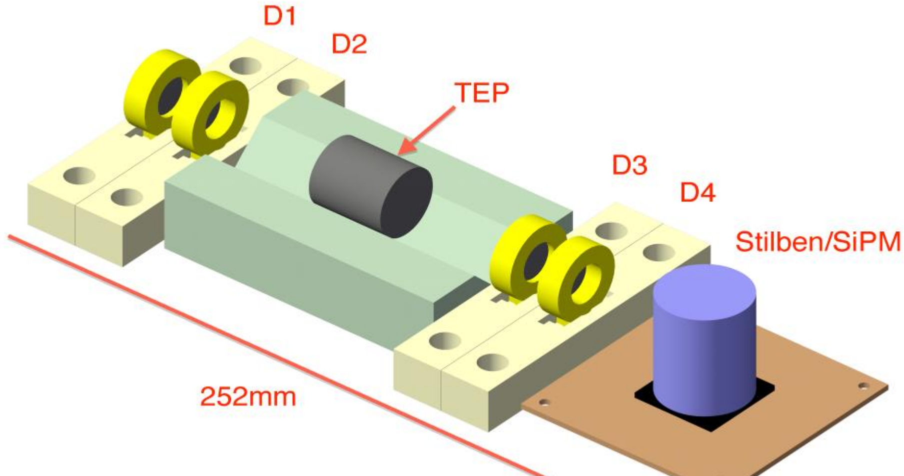

g/cm^2 Al
0.3 Lens
0.3 Bfo
1.0 Lens
1.0 Bfo
5.0 Lens
5.0 Bfo
10 Lens
10 Bfo
cSv
Days
100
80
60
40
20
0
0.0
0.1
0.2
0.3
0.4


Near Earth
Ions s⁻¹ sr⁻¹ cm⁻² MeV⁻¹
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
2
4
6
8
10
Hours
1.00 MeV
2.85 MeV
8.10 MeV
22.91 MeV
63.94 MeV
172.63 MeV
436.17 MeV
1000.00 MeV

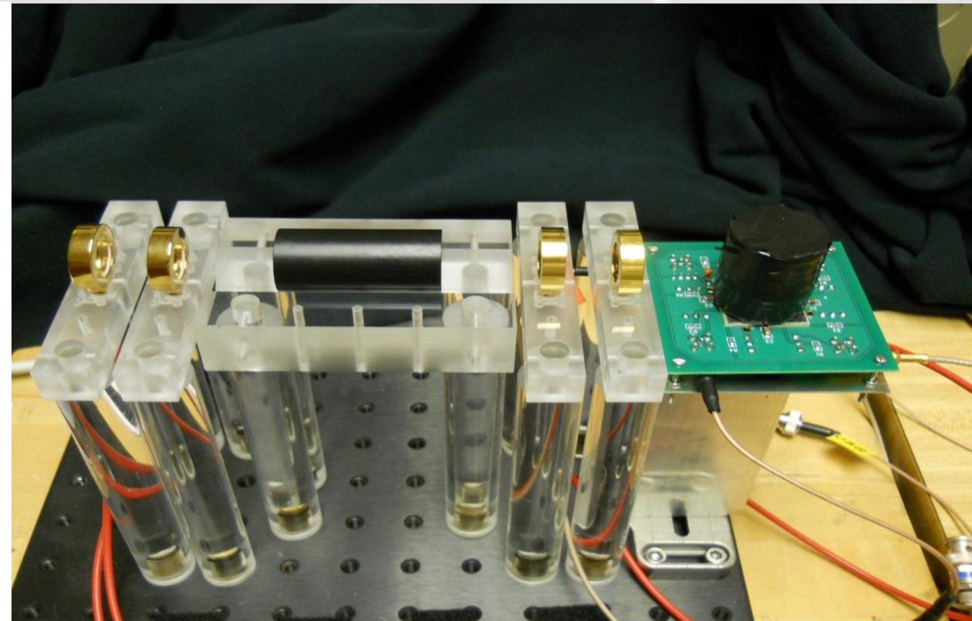

Retrograde
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
0
2
4
6
8
10
Hours

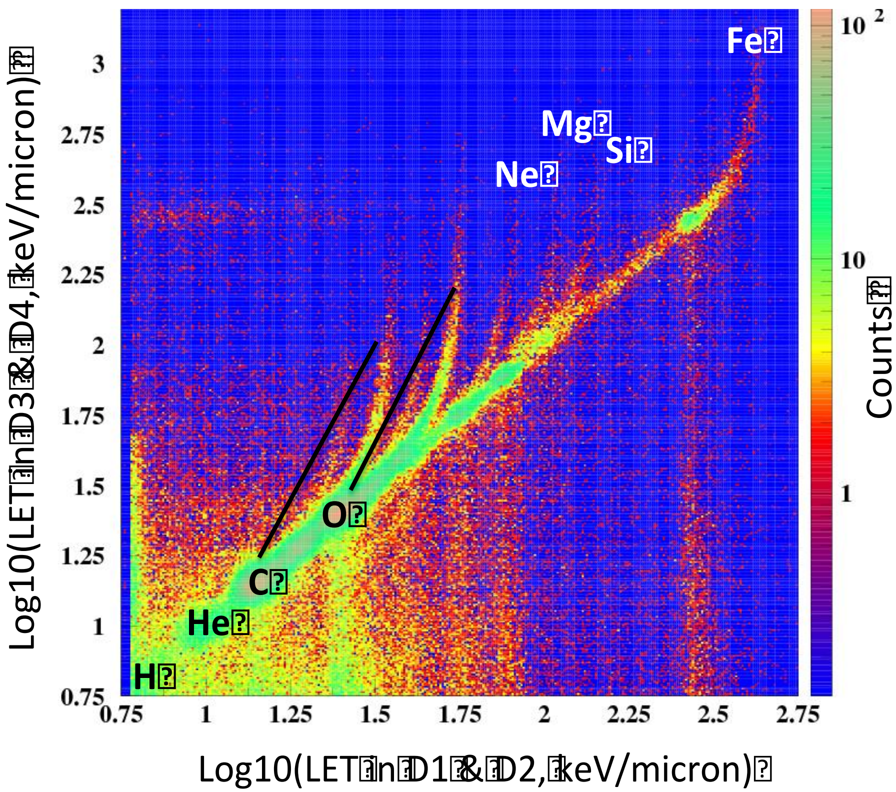

Prograde
2
4
6
8
10
Hours


See recent work by
Mertens et al.,
Tobiska et al. and Phillips et al.
36 km
30 km
25 km
20 km
16.5 km
13.5 km
11 km
1.0000
0.1000
0.0100
0.0010
0.0001
Dose Rate (cGy/day)
2009
2010
2011
2012
2013
2014
Year
Joyce et al., Space Weather, 2013

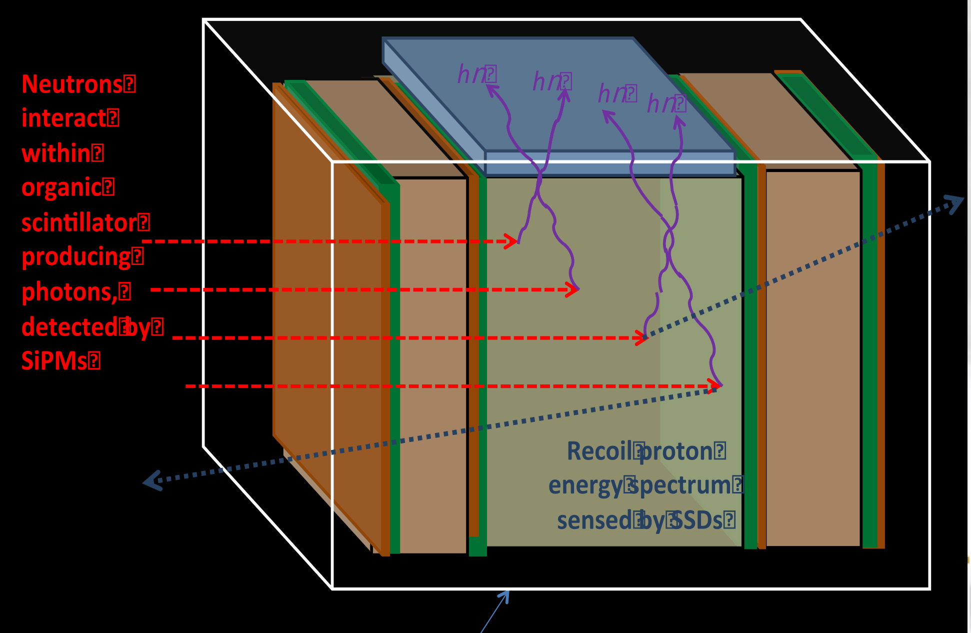


Schwadron et al., Space Weather 2013





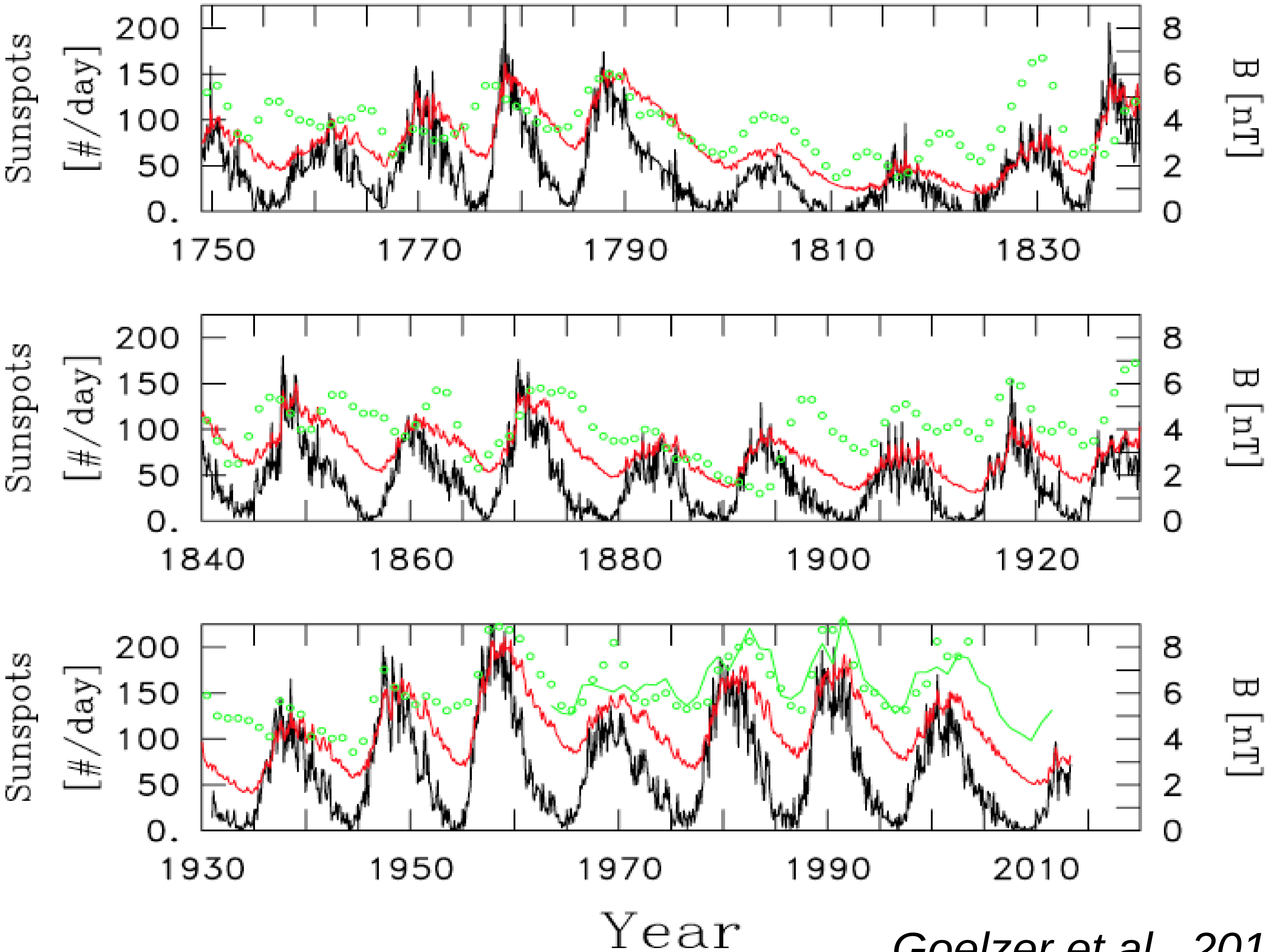
DoSEN Neutron Measurement Concept



Summary

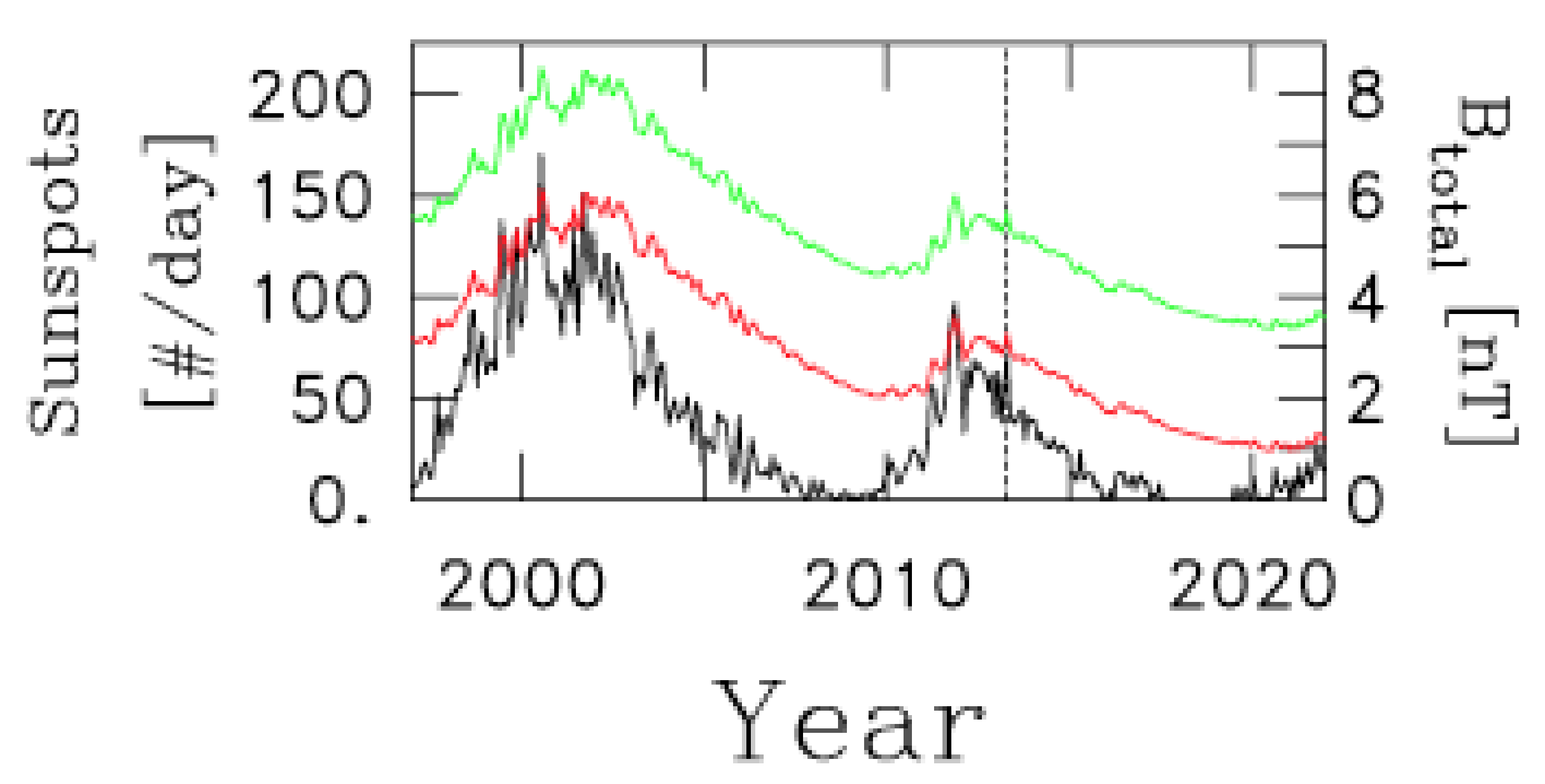
- Worsening radiation environment from anomalously low solar activity
  - Cycle 23-24 Protracted Minimum
  - Cycle 24 Mini Maximum
- Solar Maximum may be the time to perform long-duration exploration missions
- Threat of large prompt solar events (e.g., July 2012 STEREO event, Russell et al., 2012)

- **Increasingly Difficult Problem!**



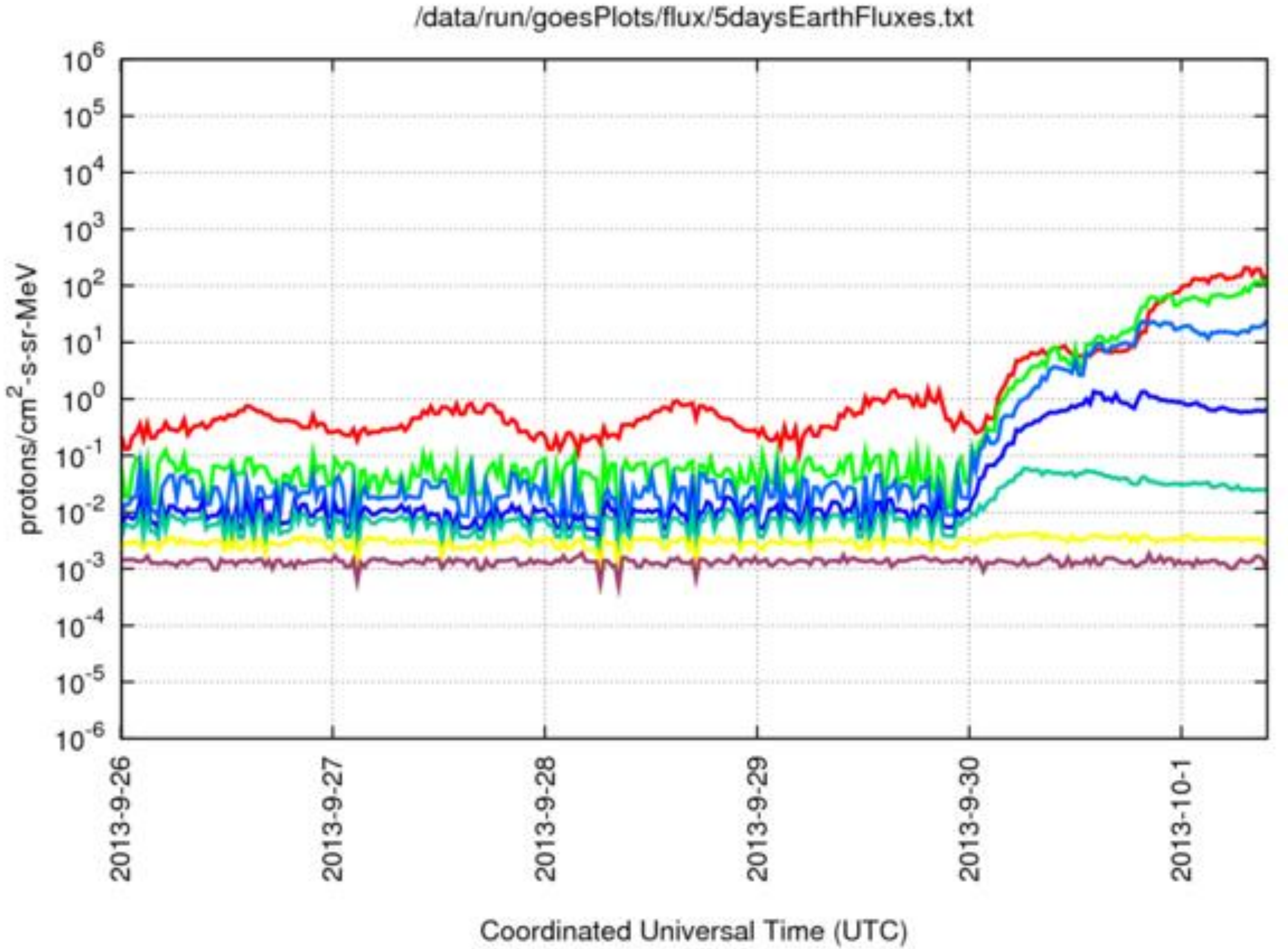
Goelzer et al., 2013

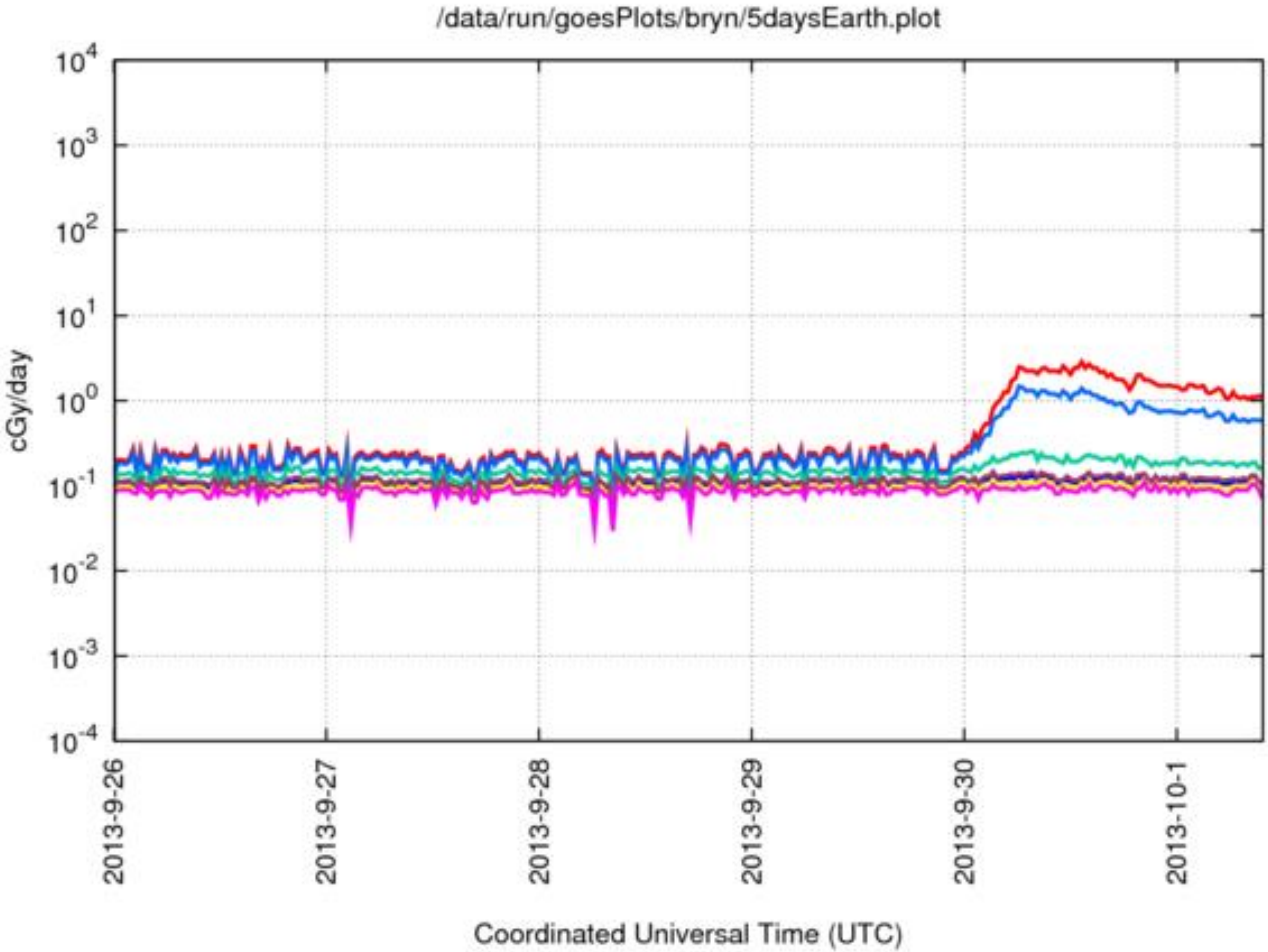
The remarkable evolving Sun



Will the next cycle also look like the Dalton minimum (1807-1840)?

Goelzer et al., 2013


/data/run/goesPlots/flux/5daysEarthFluxes.txt
protons/cm^2-s-sr-MeV
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
2013-9-26
2013-9-27
2013-9-28
2013-9-29
2013-9-30
2013-10-1
Coordinated Universal Time (UTC)



/data/run/goesPlots/bryn/5daysEarth.plot
cGy/day
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2013-9-26
2013-9-27
2013-9-28
2013-9-29
2013-9-30
2013-10-1
Coordinated Universal Time (UTC)

U. Tennessee – EMMREM Accomplishments

NNX07AC14G – L. Townsend

- Lead development of Scenario and Transport code modules
- Provided capability, in near-real-time, to calculate radiation doses and LET spectra for tissue and electronics behind spacecraft aluminum shields using "looping" BRYNTRN code
- Provided database of human organ radiation exposures for Al shielding thicknesses relevant to vehicle and habitat designs anywhere in free space or in Mars atmosphere for GCR and SEP spectra covering the entire solar cycle
- Calculations of doses, dose equivalents and effective dose for GCR and SEP protons at aircraft altitudes in Earth's atmosphere are completed. Heavy ion component calculations are in progress
- Publications (author/coauthor)

  - 10 journal articles

  - 4 invited paper presentations

  - 15 contributed paper presentations
- 3 graduate students supported

Transition to Prediction & Operations

- New ESMD/LRO Predictive Model

Task Description	Value to ESMD
(1) SEP Prediction Development	Uses CRaTER observations and existing models to **improve advanced warning of solar proton events**
(2) Radiation Environment Forecasting	Develops analysis and modeling tool combined with CRaTER observations to **extend prediction of the radiation environment well beyond low Earth orbit**, not only at Moon but also throughout the inner heliosphere, including at Earth, Moon, Mars, Asteroids, and Comets

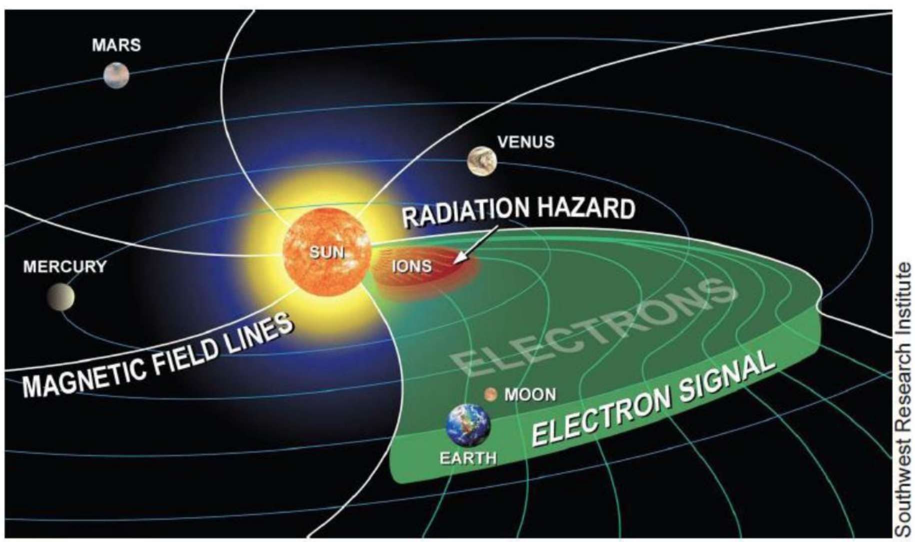


Figure from Posner et al. (2009) demonstrating how relativistic electrons racing ahead of SEP ions provide an early warning of the radiation hazard to follow up to one hour later.

Next Steps for EMMREM

- Transition to Operations and Predictive Models
- Development of Comprehensive Risk Models
- Coupling between MHD & EPREM
- Continued development of PATH into a predictive model

Modeling Large SEP Events with PATH Code

- Zank et al., AGU, 2010